INDUSTRIAL MEASUREMENT AND CONTROL

CONTROL AND MEASUREMENT, INDUSTRIAL. SEE INDUSTRIAL MEASUREMENT AND CONTROL.

In the industrial world, the rapid growth in importance of the concepts of total quality control, factory automation, safety, health and environmental management, has created a demand for major developments in measurement and control instrumentation.

Process controllers are linked to sensors and actuators and perform the automated operations. Operator keyboards, monitors and printers make it possible to measure and control all process parameters. The design of process instrumentation deals with the choice of the control variables and the implementation of the measurement system on the process. This activity has to be integrated with the design of systems of actuations and process controllers (1). Difficulties in control of a complex final process may occur if certain input-output variables are selected for a given local subsystem.

Because of the increasing needs to rationalize and economize production processes and installations, in the last years instruments have evolved from analog systems, measuring and controlling a modest number of plant parameters, to digital systems with a large number of input and output quantities. Increasing interest is especially oriented toward single-chip devices (sensors and actuators) with built-in intelligence (smart devices). They essentially help implement new applications, reducing or eliminating the need for higher-level instruments and controllers.

The use of smart devices can help not only to control the processes, but also to monitor and supervise the global production. The acquisition of multiple variables is carried out to archive information, to analyze the production processes and to improve the product quality by means of an optimized management of the plant, as required by the ISO 9000 standard. The overall monitoring allows keeping the plant operating efficiently and safely.

The design of industrial smart devices involves the choice of both a suitable transducer/actuator and an infrastructure that ensure its interfacement to a communication network. The growing international market competition requires widely accepted standards, to provide a common interface that facilitates the communication between devices from different suppliers.

PRELIMINARY REMARKS

In the industrial field, manufacturing activities involve a number of steps, all of which should be individually controlled. The performance of each step and the entire production can be improved by exchanging information between process controllers and a central controlling system, using advanced digital technologies.

Continuous controllers, widely used in the past, were based on analog electronic devices and generally perform PI (Proportional-Integral) and PID (Proportional-Integral-Differential) control loops. The operation of complex industrial processes requires the adoption of suitable measurement and control instruments and techniques. As an example, advanced digital control techniques for nonlinear or time varying processes, such as those based on state observer or adaptive control, need to increase both the number of process variables to measure and the speed of execution.

The design of a measurement and control system requires, then, the analysis of two opposite aspects: the centralization of command and supervision functions and the decentralization of processing functions. The actual tendency is to move away from older, centralized plant control strategies, to distributed control in the field. In the new manufacturing industries, information is exchanged between small devices co-operating for each production process control, such as sensors, actuators and local controllers. An important issue is that, at this level, the data transmission requires a deterministic response time.

The recent development in integrated circuit technology and the availability of cheap analog-to-digital (A/D) and digital-to-analog (D/A) converters and microprocessors, have led to the implementation of microprocessor-based process sensors and actuators. In a smart sensor the sensing element generally has an analog output, which is converted by an on-board A/D included on the sensor package to improve the modularity and flexibility and reduce the noise on the signal transmission. The digital output signal can be processed by an on-board device, to extract information by means of computing algorithms (smoothing, curve-fitting, convolution) and a calibration procedure can also be implemented (2).

To connect smart sensors and actuators to the controllers in industrial environments, reliable communication networks could be implemented. This is not a simple task. Some features of industrial communication networks are quite different from those applied for business information systems, because of the different application and the different (harsh and hazardous) installation environment. They are generally designed to operate with a wide operating temperature range, high degree of vibration, high level of signal noise. The emphasis is for highspeed and secure transmission of typically small information packets.

In the past the communication was generally carried out by means of point-to-point links transmitting analog signals. Today the tendency is to replace them by a single communication medium (*fieldbus*). This is essentially a LAN (Local Area Networks) for instruments used in process control and manufacturing automation applications, with a built-in capability to distribute the measurement and control applications across the network. In the past, proprietary fieldbuses were frequently used, but today all systems in design are open standard systems. In this way the user can select the best and most economical products from a wide variety.

To implement an industrial network it is necessary to identify a suitable communication protocol, which defines how computers identify one another, the form that the data should take for the transmission, how the receiver processes data, and how to manage lost or damaged data packets. A vast number of technologies and products have been developed and many more are under development.

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There are a number of protocols generally used outside the industrial field, such as the common protocols associated with the Internet and LANs. Their use for industrial applications presents some problems, also because measurement and control tasks are not confined to individual processors, but distributed across a number of controllers. Moreover, to implement real-time systems, these networks must support synchronization, multiple priority messages, and multicast message transmission.

However, both suppliers of controls and instrumentation and end users continue to seek a single international fieldbus standard.

Interfacing transducers to all control networks and supporting the wide variety of protocols is time-consuming and costly for manufacturers. To simplify this problem a standardized connection method to interface smart transducers to the existing control networking technology has been proposed.

INDUSTRIAL MEASUREMENT SYSTEMS

Sensors for Industrial Measurements

In continuous process industries the primary task is the measurement and control of process variables. Many different types of devices are available, to measure different quantities, e.g. pressure, flow, level and temperature.

Pressure. Pressure is generally sensed by elastic mechanical elements, such as plates, shells and tubes that will deflect, producing either displacement or strain. The curved Bourdon tube is composed of a springy material that tends to straighten up when pressure is applied. Bellows sensors are typically made using metallic springs that form the sides of a box connected by a rod to a transducer. They displace axially when pressure is applied, producing an electric signal proportional to this displacement.

A diaphragm is a thin circular plate fastened continuously around its edge. The application of a pressure generates a strain that is sensed by strain gauges. These sensing devices are based on the principle that a change in a material's elongation or compression creates a change in electrical resistance, generally converted into voltage by means of a deflection-type Wheatstone bridge. Some special types of pressure sensors include electro-optic sensors, which use a diaphragm to confine the light emitted by a light-emitting diode (LED) and received by a photodiode. Pressure sensors are widely used in different applications for the measurement in the range of a few kilopascal to over a hundred megapascal. Most sensors provide accuracy between ±0.5% to ±1.5%. Temperature variation can increase the sensor uncertainty, even if many devices include a circuitry to compensate for thermal effects.

Today smart pressure sensors have been introduced. They calculate and dispatch the result directly in engineering units. The result is compensated for temperature and linearity over their entire operating range.

Flow. Flowmeters are used in practically all industries, to measure the flow of gases and liquids. In some measurement devices the fluid is forced to flow through a pipe restriction or a curved pipe. The change in its velocity generates a pressure difference proportional to the flow (Bernoulli's principle), which is measured by a pressure sensor.

In the flowmeters that use a turbine-type rotor meter, the flow velocity is converted into an angular velocity by the turbine. The speed of the wheel is converted into electrical analog (by a tachometer) or digital (by an angular encoder) signals. Turbine meters are widely used when high accuracy measurements should be carried out.

In the Vortex meters a vortex-shedding body is immersed into a pipe through which a fluid is flowing. The surface frictional forces of this body produce vortices in the fluid. This will give to the fluid an oscillatory motion, proportional to volumetric flow rate. The frequency of vortex formation is converted to an electrical signal through a signal-conditioning unit.

Faraday's law is the basis for the operation of the electromagnetic flowmeter. A conductive, or slightly conductive, fluid flowing through a transverse magnetic field has an increasing electromotive force induced in it by an increasing flow velocity. Magnetic field is created by an electromagnet, excited by a sinusoidal ac (alternating current) or pulsed dc (direct current) current. Its main advantages are its obstruction free design and its high accuracy over wide flow ranges.

Ultrasound is used by some flowmeters to measure flow rate of any sonically conductive homogeneous fluid. A transducer sends ultrasound, at a particular frequency, through the fluid, where transmit time is measured by a second transducer on the far side. The instrument is available in portable form, using clamp-on transducers.

Level. Level sensing technologies can be classified as mechanical, electrical, ultrasonic and nuclear.

Level can be measured in a simple way by a float device attached to an arm that moves across a resistive element, where resistance changes proportionally to liquid level.

In a buoyancy sensor the float does not actually move, rather a pressure sensor transduces the force acting on it due to buoyancy. The liquid density must be unvarying.

Conductive and capacitive liquid level sensors use metal (stainless or titanium) probes which are configured to provide a measure of either resistance (for conductive liquids) or capacitance (for nonconductive liquids) both of which are proportional to liquid level. Capacitance is generally measured by an impedance bridge, excited by an ac voltage at 400 Hz to 10 kHz.

Ultrasonic sensors generally employ the reflectance properties of sound energy to provide measurement of liquid level. Ultrasonic waves produced by a piezoelectric oscillator located on the top of the tank get reflected back at the surface of the liquid. The measurement of the transit time supplies information about the distance between the sensor and the liquid (3).

Similar to ultrasonic systems, microwave sensors make use of reflection of a microwave pulsed signal at a frequency around 10 GHz. This technique can be used to detect level of solids and solid/liquid interfaces. The only negative aspect of this instrument is its high cost.

Nucleonic level instruments measure the attenuation or absorption of gamma rays as they pass through the tank and the product. A radioactive source is located at one side of the tank, while one or more detectors are located at the opposite side. The main drawbacks of this technique are the high cost and the problem of safety, while the main advantage is the possibility to install the system outside of the tank.

Load cells or strain gauges can he used to measure level by weighing a tank of known geometry. This sensing technique can be used for both liquids and solids of known specific weight. The tank can be mounted in a weighing arrangement in which its tare is balanced by ballast mass equivalent to the tare weight of the tank.

Temperature. Thermocouples and Resistance Temperature Detectors (RTDs) are the most utilized temperature sensors in industry.

RTDs operate on the principle that the electrical resistance of a metal wire changes nearly linearly with temperature. Platinum is the preferred metal chosen for a variety of applications. RTDs require a signal conditioner to convert the resistance into an electrical voltage or current proportional to the sensed temperature.

A thermocouple is based on the Seebeck effect. Two dissimilar metals are joined together at the measuring point. When this sensing junction is heated, with respect to the other reference junction, an electromagnetic force proportional to the temperature differences between the two junctions appears. A signal conditioning circuit is required to convert the low level (some millivolt) voltage to a higher level signal for transmission to the measurement system.

Radiation pyrometers are used in high temperature applications, especially in the metal industry. They use a remote noncontacting measurement technique, based on the detection of thermal radiation emanating from the device under measurement (target). Fiber optics can be used to transmit radiation to a detector that cannot be directly exposed to the target.

Field Device Connection Systems

In industry the process devices, such as controllers, transducers, actuators and sensors, are called *field devices*. The field devices really in use can be classified in three groups (Fig. 1):

- devices with analog I/O;
- hybrid devices with analog and digital I/O;
- devices with digital I/O.

The first type of devices is generally linked by point-to-point analog links.

The second type of devices is linked with both analog and digital transmission links. Analog transmission requires a point-to-point link, even if additional information can be transmitted, enabling the digital transmission.

Digital devices generally require special hardware interfaces and software drivers, which slow down the devices. The choice of the signal type generally involves: data rate, accuracy and cost.

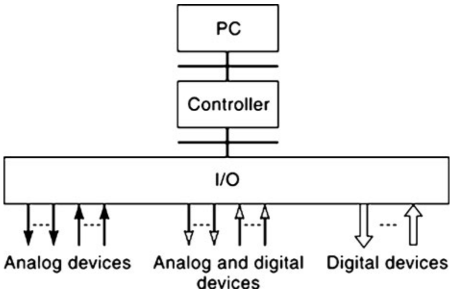

Figure 1. Field devices.

Analog Transmission. Analog signal transmission is generally carried out by taking different approaches:

- dc voltage transmission;
- dc current transmission;
- ac frequency transmission;
- transmission of a signal generated by applying pulse modulation techniques.

Voltage Transmission. In case of dc voltage transmission, the transmitter generally includes a front-end amplifier, to buffer and scale the input, and a line driver to send the voltage signal. The voltage receiver can also include a buffer amplifier. The transmitter can be locally powered (Fig. 2) or remotely powered (Fig. 3), by using a four wire link.

This technique presents the disadvantages of transmission errors due to the line resistance and to the series and common mode noise signals, because of inductive and capacitive coupling.

Moreover, if the signal return line is grounded both at the transmitter and at the receiver, a difference in potential between the two grounds may cause a circulating current, generating a noise signal that corrupts the transmitted information.

Current Transmission. The current loop, introduced in the 1960s, is the predominant analog transmission system. This is not an international standard, even if it is widely used in the industrial field.

In this link data are transmitted in only one direction. A loop links transmitter and receiver devices. The current transmitter includes a front-end amplifier, to buffer and scale the input, and a voltage-to-current converter (V/I), which generates the loop current. The value of the circulating dc current is in the range of 0 to 20 mA and generally is linearly related with the transmitted quantity. The lower value of the range frequently is set to 4 mA, to guarantee against undetectable possible loop interruption. In this case the transmitters generally embody two current sources, one supplying a constant 4 mA output and the other generating a 0 to 16 mA output, proportional to the input voltage signal.

The transmitter can be locally powered (Fig. 4) or loop powered (Fig. 5), by using in this case the same two-wire loop both for signal and power transmission.

After current transmission, voltage signals can be easily reconstructed by the receiver, which embodies a current

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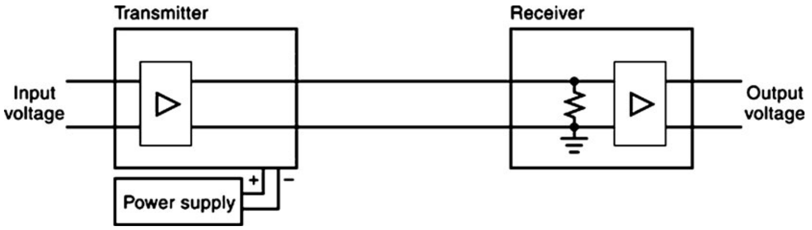

Figure 2. Locally powered voltage transmission.

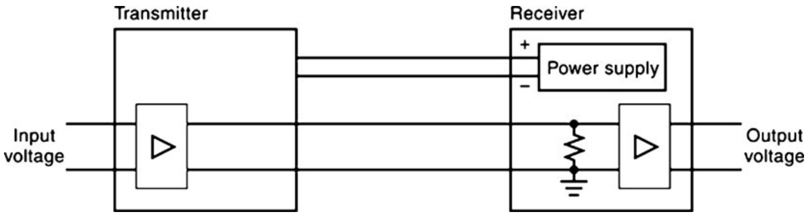

Figure 3. Remotely powered voltage transmission.

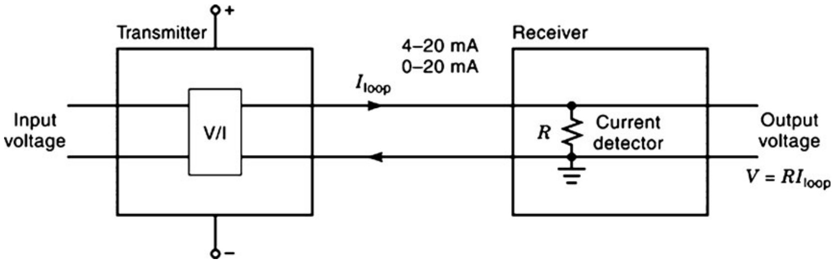

Figure 4. Locally powered current transmission.

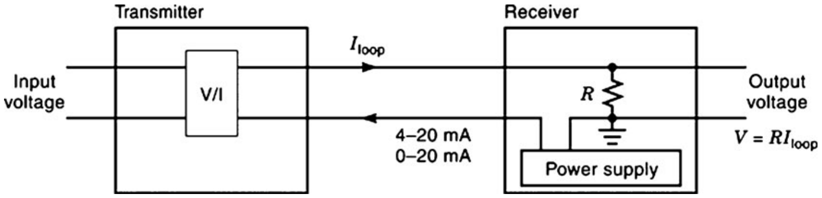

Figure 5. Remotely powered current transmission.

detector circuit. The signal is evaluated by considering the voltage drop across a low-valued resistance (250 Ω, for 1 to 5 V output). An operational amplifier can also implement the current-to-voltage converter (I/V). In some cases the current can be directly used to drive an indicating instrument. More than one receiver can be linked to the same transmitter. The main advantage of this technique is the rejection of the common-mode noise and the elimination of the problem produced by ground loops. Current signals are not as susceptible to noise as voltage signals. In fact, the low impedance of the circuit presents the advantage of a reduced noise power level. If a current is magnetically coupled into the connecting wires in the transmission of the signal from a current source, no significant change in the signal current will result.

Other advantage is the elimination of the voltage attenuation effect of cable resistances, because the information is transmitted as a current signal. It is also economical and interchangeable. The main current loop disadvantage is that the controller receives from the instrument a piece of information related to only one quantity of the process under measurement. The maximum transmitter voltage essentially limits the loop length, which must be greater than the voltage drop along the line and the receiver input stage. An error source for this kind of transmission is caused by the insulation resistance of the line, which can shunt the loop current, reducing the current at the receiver. Typical accuracy is ±0.5%.

Frequency Transmission. Signals transmitted as frequency present the advantage that the transmission line influence on both signal amplitude and phase can be disregarded. As shown in Fig. 6, the transmitter includes a voltage-to-frequency converter (V/f), a device that generates a train of pulses or square waves at a frequency proportional to the input voltage, generally operating asynchronously (4). The frequency range mainly depends on the medium bandwidth. Frequency transmission requires two wires. The V/f converter can share the same two wires both to send the pulse train (as a current signal) and to receive the supply voltage.

The receiver can be a frequency-to-voltage converter (f/V), which provides an analog voltage, proportional to the number of pulses occurring in a given time. It also can be a counter, which supplies a digital output representing the averaged input during a fixed period of time. The resolution obtained can in theory be increased indefinitely by increasing the measuring time, even if noise and drift limit it.

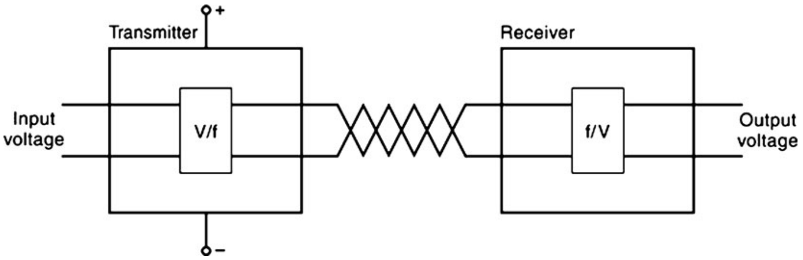

Figure 6. Frequency transmission.

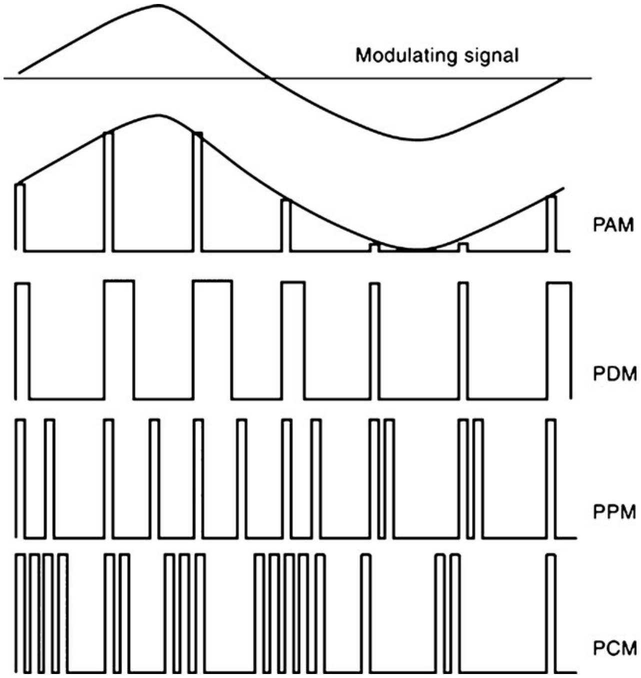

Figure 7. Basic modulation waveforms used in pulse transmission systems.

The advantage of this transmission technique is to transmit a signal through a noisy environment without interference, because frequency signals are less susceptible to interference.

Pulse Modulated Transmission. In pulse modulation techniques, sequential samples of a measurement signal are converted to a series of pulses (pulse train). The advantage is a good signal-to-noise ratio transmission. The main basic methods include:

- pulse-amplitude modulation (PAM);
- pulse-duration modulation (PDM);
- pulse-position modulation (PPM);
- pulse-code modulation (PCM).

In PAM the transmitted (modulating) signal determines the pulse amplitude: the pulse height correspond to the instantaneous amplitude of the transmitted signal (see Fig. 7). The pulse repetition period is constant. The receiver demodulates the pulse waveform, e.g. by a low-pass filter, to reconstruct the modulating signal.

In PDM the transmitted signal determines the duration of pulses with constant amplitude. Pulse repetition period is constant.

In PPM the instantaneous amplitude of the transmitted signal changes the pulse data rate. The pulses present constant amplitude and constant width, but a nonuniform repetition period.

In PCM the transmitted signal is sampled, converted by means of an A/D converter and serially transmitted in terms of pulses and spaces.

Analog/Digital Transmission. Even though interference can be problematic in sending analog signals, this kind of transmission is widely and successfully used in industry. The effects of noise can be reduced with careful engineering design, proper installation, routing techniques of wires and cables, and shielding and grounding.

The current loop is still the most cost-effective, easy-to-use diffused link, mainly because change to a digital bus can represent a very expensive operation.

For this reason hybrid solutions have been proposed and applied, such as the transmission of digital data over the analog current loop. Devices implementing this transmission are called smart devices and generally implement the HART protocol. HART is an acronym for Highway Addressable Remote Transducer. It makes use of the Bell 202 Frequency Shift Keying (FSK) standard to superimpose digital signals at a low level on top of the 4 to 20 mA (logical “0” frequency is 2200 Hz and logical “1” frequency 1200 Hz). As the digital FSK signal is phase continuous, there is no interference with the 4 to 20 mA signal.

The HART protocol communicates without interrupting the 4 to 20 mA signal and allows a host application (master) to get two or more digital updates per second from a field device (data rate is 20 kb/s). This allows transmitting additional information, even if at low speed. In this case the analog transmission is generally used for process control, while the digital transmission is used to configure the remote device or for diagnostic purposes.

A two-way communication, to/from a smart field instrument, can take place. The bi-directional transmission can be carried out by means of two pairs of cables. The first loop links a transmitter at one end and a receiver at the other end. The other one implements the transmission in the opposite direction.

The data transmission is serial, with the same data encoding used for the RS-232 standard (1 start bit, 7/8 data bits and 1/2 stop bit). A two-dimensional error checking is implemented.

The system allows for up to 256 floating point 32 bit variables per device, using the format of the IEEE 754 Standard for the Binary Floating-Point Arithmetic. The wiring topology is point to point for simultaneous analog and digital transmission or digital only. If only HART devices are present, they (up to 15 devices) can be linked together on a shared bus, implementing a multidrop network for only digital transmission. The maximum twisted pair-length is about 3 km.

The problem is how smart devices will change into full digital systems. The smart protocols operate at low data rates, which are sufficient for programming but not for transmitting the process value. This is for applications that require an update time of some hundreds of milliseconds. Then the implementation of a full digital fieldbus will require a substantial investment.

Smart technology is a good choice when there are only a few measuring points. The small price difference is justified by the better maintenance. For larger industrial plants, with a great number of measuring points, or for high-speed processes, the full digital solution is better.

Digital Transmission. Many devices use the EIA/TIA (Electronic Industries Alliance/Telecommunications Industry Association) Standards for serial data transmission, which specify the electrical characteristics of the interchange signals and associated circuitry, the interface mechanical characteristics and a functional description of the interchange circuits. The software protocol is not specified.

A widely used standard is the RS-232-C (commonly called RS-232), released in 1969 (5). At that time, the EIA referred to all of its standards as Recommended Standards and prefaced the number with "RS". In 1987, EIA-232-D was released, with little changes. In 1991, EIA/TIA-232-E was released (the EIA began to work with the TIA on standards that concern telecommunications, so TIA gets its name in the standard too). The last version is the F revision (6). RS-232 uses a single-ended (unbalanced) communication signal.

The limitation on transmission cable length has been partly overcome with the RS-423-B interface (7), which still adopts an unbalanced line, as the RS-232. Unbalanced drivers and differential receivers are used to overcome the problem of crosstalk, caused by capacitive coupling between adjacent lines (e.g. sending and receiving lines). Only one end of the transmission line is grounded, to eliminate ground loops. The data rate is 120 kbps with a line length of 30 m and 3 kbps at 1200 m.

The RS-422 standard (8) uses a differential (balanced) communication signal. Differential transmission exhibits greater noise immunity, reduced line radiation (less RF interference), improved speed capabilities and longer distances as compared with single-ended transmission. An RS-422 line allows for only one way (simplex) communication. Each driver can drive up to 10 receivers.

The RS-485 standard is a widely accepted industrial party-line network (several communication stations on the same twisted pair of wires) for long distances (1200 m) (9). It is an improvement of the RS-422 because it increases the number of connected devices from 10 to 32. This standard facilitates half-duplex multipoint communication. RS 485 transmission technology is very easy to handle. Installation of the twisted pair cable does not require expert knowledge. The bus structure permits addition and removal of stations or step-by-step commissioning of the system without influencing the other stations. Later expansions have no effect on stations that are already in operation. All devices are connected in a bus structure. Up to 32 stations (master or slaves) can be connected in one segment. An active bus terminator at the beginning and end of each segment terminates the bus. To ensure error-free operations, both bus terminations must always be powered. Many vendors have designed a switchable bus termination in their devices or plug connectors.

The maximum cable length depends on the transmission speed, as reported in Table 1 for a cable with a capacitance of about 30 pF/m. The specified cable length can be increased by the use of repeaters (line amplifiers). When more than 32 stations are used, repeaters must be used to connect the individual bus segments. The use of more than 3 repeaters in series is not recommended.

Use of shielded data lines is preferred to twisted lines to achieve high system immunity in environments with high electromagnetic emission. Shielding is used to improve electromagnetic compatibility (EMC). In addition, it is recommended that the data lines be kept separate from all high-voltage cables.

The main features of the EIA/TIA Interface Standards are summarized in Table 2.

Wireless Transmission and Wireless Sensor Networks. Some smart sensors usually consist of a sensor (including a specific conditioning circuitry), a processing unit, a communication device (usually radio or optical transceiver) and a power source (usually a battery). They are used to monitor data that would be difficult or expensive to monitor using wired sensors.

Smart sensors and sensor networks are widely applied into almost all industries. An important development is the wireless sensor network, a network of spatially distributed autonomous sensors, machine controllers, RF transceivers and user interface devices with at least two nodes communicating by means of a wireless transmission (10). Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and bandwidth. A component of these systems is the base station that acts as a gateway between sensor nodes and the end user.

As a progress of the extreme miniaturization, wireless sensors are increasingly becoming monolithic devices in which the sensor element, smart signal conditioning electronics and wireless transceiver are integrated within the device.

A limit of wireless devices is the power. The batteries are problematic for large-scale wireless applications, they have to be monitored for charge and useful lives vary depending on the operating environment. Furthermore, devices must be accessible for battery replacement.

Self-powered sensors are being developed extensively and the emergence of those with energy-harvesting capability could eliminate the need for frequent battery changes and facilitate autonomous sensor networks. Potential en-

Table 1. Distances based on transmission speed for a cable

Baud rate (kbit/s)	9.6	19.2	93.75	187.5	500	1500	12000
Distance [m]	1200	1200	1200	1000	400	200	100

Table 2. Summary of EIA/TIA Interface Standards

	RS-232	RS-423-B	RS-422-A	RS-485
Mode of operation	Single-ended	Single-ended	Differential	Differential
Number of transmitters and receivers	1 Tx 1 Rx	1 Tx 10 Rx	1 Tx 10 Rx	32 Tx 32 Rx
Cable length (m)	15	1200	1200	1200
Data rate (bit/s)	20 k	120 k	10 M	10 M
Maximum common mode voltage (V)	±25	±26	6 to −0.25	12 to −7

ergy sources include light, vibration, thermal gradients, pressure differential, motion, and piezoelectric (from manual depression of a push-button switch) present in the environment (11).

Today radio-frequency (RF) links are available in several varieties. Some RF devices operate on licensed frequencies, the ISM (instruments, scientific and medical) band. Some unlicensed narrow-band units operate in the 900 MHz and 2.4 GHz bands, at distances to 2 km. With antennas or repeaters, distance can reach 150 km, achieving full-duplex uncompressed data rates of 115 kbps with a response time of 5 to 15 ms between units. When interference is present in this band, the spread spectrum transmission technique is applied.

The security is not a major consideration with wireless sensors located within a factory or plant, because they are located in areas that are physically secure and the range of communication for any device is small (typical range is a 70 m radius).

The most used transmission standards are *Wi-Fi*, based on the IEEE 802.11 specifications with suffixes 'a (54 Mbit/s),' 'b (11 Mbit/s),' 'g (54 Mbit/s)' (12). Excepting 'a,' all use 2.4 GHz. 802.11b uses DSSS (Direct Sequence Spread Spectrum) modulation, a method of transmitting a signal by spreading it over a relatively wide part of the available frequency spectrum. 802.1 1b divides the spectrum into 11 overlapping and 3 non-overlapping channels whose center frequencies are 5 MHz apart and about 22 MHz wide. As 802.11a, the 802. 11g specification employs Orthogonal Frequency Division Multiplexing (OFDM) to obtain higher data speed. Unlike 802.11a, 801.11g provides a CCK (Complementary Code Keying) modulation too for 802.1 1b compatibility at data rates of 1, 2, 5.5 and 11 Mbp.

Bluetooth is based on IEEE 802.15.1 and using 2.4 GHz frequency, provides short distance communications between 1 master and 7 slaves. Bluetooth supports a very short range (approximately 10 meters) and relatively low bandwidth (1 Mbps). A pseudo-random frequency-hopping technique combats interference and signal fading on 79 available channels (1 MHz width), doing 1,600 hops/s. Each packet has its own channel, so if a packet is poorly transmitted it will be re-transmitted on another channel. Interconnection is possible, forming a piconet: one master device and up to seven connected slaves. Any device can be a master of one piconet and a slave of another (13).

ZigBee is a more recent RF standard, based on IEEE 802.15.4, specifically developed for low power, low data rate networks. It operates at either 2.4 GHz or 900 MHz with a simple protocol (protocol stack is one-third the size of Bluetooth and 802.11 protocols) and offers high reliability (each transmission burst is acknowledged). It provides a security approach to ensuring reliable and secure data transmission, with a 128-bit AES (Advanced Data Encription).

The Table 3 reports a synthesis of the main feature for the different standards.

Smart Field Devices

The smart field modules generally have a built-in processor that performs A/D and D/A conversions, storage of calibration curve and conversion factors, environmental parameter compensation and management of the communication. Smart sensors can self-monitor for any aspect of their operation, and can be re-ranged in the field allowing users to substitute several traditional sensors. A smart sensor includes features such as on-board diagnostics and communication capability and provides information to a monitoring system and/or operator to increase operational efficiency and reduce maintenance costs.

Their design involves the choice of both a suitable sensor/actuator and an architecture that ensure its interfacement to the communication link. Many communication network or fieldbus are currently available, each with its own peculiarities for a specific application class. An important issue is that, when the number of sensors and actuators increases, further special features are required, such as self-identification of the devices, self-configuration, ease upgrades and maintenance, remote self-calibration.

Without an openly defined standard, interfacing to all control networks and supporting the wide variety of protocols is time-consuming and costly for manufacturers. Implementing a special interface for each sensor is impracticable for the user. A reduction of the design constraints is represented by the possibility to choose the sensors/actuators (hardware and software) that do not depend on a specific control network. This implies that the support for multiple networks in not a stringent requirement for these devices, reducing so costs and complexity. At the network level this implies that the migration to a different network is simplified.

Table 3. Summary of main wireless standards

Feature	Wi-Fi IEEE 802.1 lb	Bluetooth IEEE 802.15.1	ZigBee IEEE 802.15.4
Range	100 m	10 m or 100 m	70-300 m
Number of nodes	32	7	65,000
Data Rate	11 Mbps	720 Kbps	250 Kbps
Data Latency	up to 3 s	up to 10 s	up to 30 ms
Complexity	Very Complex	Complex	Simple
Extendibility	Roaming possible	No	Yes
Data protection	32-bit CRC	16-bit CRC	16-bit CRC
Security	MIC (Message Integrity Check)	64- 128 bit WEP (Wired Equivalent Privacy)	128 bit AES
Battery life (days)	0.5–5	1–7	100–1000

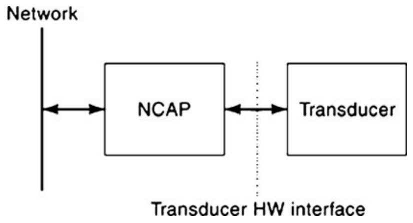

Figure 8. A 1451.1 remote smart transducer block configuration.

In the smart sensor field a vast number of technologies and products have been developed and many more are under development.

IEEE 1451 Standard. A IEEE/NIST working group has proposed the IEEE 1451 family of standards, with the objective to utilize the existing control networking technology and develop standardized connection methods to interface both smart sensors or actuators (transducers in the standard), isolating their choice from the choice of the network.

The IEEE 1451 includes four published substandards, from 1451.1 to 1451.4, while three new projects, the P1451.0, P1451.5 and P1451.6, are under development.

The *IEEE 1451.1* defines a Network Capable Application Processor (NCAP) model, suitable to work with different networks (14). This hardware-independent model contains blocks, services and components, specifies interactions with the transducer and forms the basis for implementing application code executing in the processor. The NCAP hardware consists of a microprocessor and its supporting circuitry, as well as hardware implementing the physical layer of the attached network and the input/output (I/O) interface to the transducer. The block representation of this kind of remote smart transducer is shown in Fig. 8.

The *IEEE 1451.2* standard defines a digital interface, compatible with the 1451.1 information model standard, for connecting transducers to microprocessors (15). It defines hardware and software blocks that do not depend on specific control networks. The main objectives of IEEE 1451.2 are to:

- enable plug and play at the transducer level by providing a common communication interface for transducers;
- enable and simplify the creation of networked smart transducers;
- facilitate the support of multiple networks.

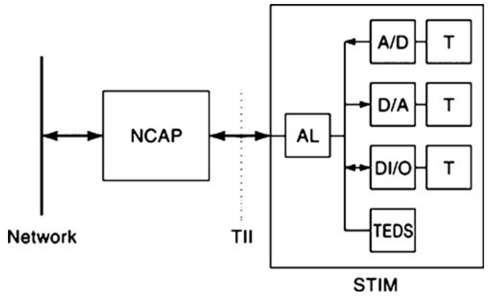

Figure 9. A 1451.2 remote smart transducer block configuration (AL: address logic, A/D: analog-to-digital converter, D/A: digital-to-analog converter, DI/O: digital input-output, T: transducer).

This standard embodies different elements (Fig. 9).

- The Smart Transducer Interface Module (STIM). This is a remote smart transducer node controlled by the NCAP, which interfaces the transducer to the control network. NCAP can also provide local intelligence to the system.

A STIM can embodies up to 255 transducer channels, each of which is described by an electronic data sheet. The interface lines connecting the STIM and the NCAP are:

- 4 data signals: DOUT (data transport from STIM to NCAP), DIN (Address and data transport from NCAP to STIM), DCLK (Positive-going edge latches data on both DIN and DOUT), NIOE (to signal that the data transport is active and to delimit the data frame);
- 1 trigger signal: NTRIG;
- 4 support signals: POWER (5 V power supply), COMMON (common or ground), NACK (to acknowledge both trigger and data), NSDET (used by NCAP to detect the presence of STIM);
- 1 interrupt signal: NINT (used by STIM to request service of the NCAP).

The data is passed to the NCAP and from the NCAP to the rest of the system. Further processing of this data may take place both in the NCAP and in other processors in the larger system. Data output by the STIM may be in different formats.

The STIM technology can also be used in different applications, such as portable instruments and data acquisition cards.

- The Transducer Electronic Data Sheet (TEDS). This is a memory area embodied in the STIM, used to fully describe the STIM itself and the type, operation, and attributes of transducers. By embodying the TEDS into the STIM, the measurement aspects are located on the STIM side of the digital interface, while the application related aspects on the NCAP side. It does not specify how the TEDS data is used in applications, instead it provides the TEDS for specifying the combination of transducer, signal conditioning, and signal conversion to the rest of the system.
- The Transducer Independent Interface (TII). This is a serial digital interface between STIM and NCAP, used to read/drive the transducer output/input, configure it and read its electronic data sheet. TII is a 10-wire synchronous serial I/O bus, based on the Serial Pheriperal Interface (SPI). It includes different functions, such as triggering, byte transfer, read/write protocol. The protocols, timing, and electrical specifications are defined so as to ensure robust data transport between different combinations of STIMs and NCAPs.

In the IEEE 1451 the word smart transducer is used to denote a device that:

- it is described by the Transducer Electronic Data Sheet (TEDS);
- uses digital control and data signals;
- provides triggering, status and control functions.

The triggering function provides means for an NCAP to send to a STIM a command for an action to take place (the trigger signal), and for the STIM to signal the time when the action occurred (trigger acknowledgment). For example, the action may be that a sensor channel samples new data.

The IEEE *P1451.3* proposes a standard digital interface, the Transducer Bus Interface Module (TBIM) to connect multiple, physically separated transducers in a multidrop configuration (16). There are currently no defined independent standards for interfacing multiple physically separated transducers that allows time synchronization of data. It will define the TEDS format, the electrical interface, channel identification protocols, hot swap protocols, time synchronization protocols, and the read and write logic functions used to access the TEDS and transducer data. It can be used in applications where it is hard or impossible to locate the TEDS with the transducer, or in applications where it is not easy to install a NCAP for each transducer.

The main objective of *IEEE P1451.4* is to establish a standard that allows analog transducers to communicate digital information (for the purposes of self-identification and configuration) with an IEEE 1451 device (17). To solve this problem, in the past some manufacturers have proposed various proprietary solutions, without gaining a market success. This standard define the protocol, the interface and the format of the transducer TEDS. It will not specify the transducer design, signal conditioning, or the specific use of TEDS. The transducer embodies a Mixed Mode Interface (MMI), a master-slave multidrop serial links connection to a STIM with MMI capability, the Mixed-Mode Smart Transducer Interface Module (MSTIM), as shown in Fig. 10.

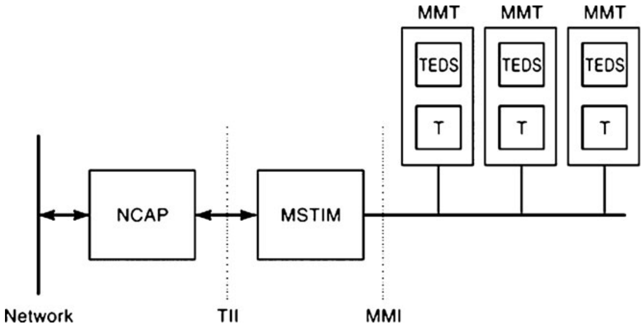

Figure 10. A 1451.4 remote smart transducer block configuration (T: transducer, MMT mixed-mode transducer).

The *IEEE P1451.0* defines a set of common commands, common operations, and TEDS for the family of IEEE 1451 smart transducer standards. Through this command set, one can access any sensors or actuators in the 1451-based wired and wireless networks. The functionality is independent of the physical communications media between the transducers and the network node called Network Capable Application Processor (NCAP). This makes it easier to add other proposed physical layers in the future.

IEEE P1451.5 defines a transducer-to-NCAP interface and TEDS for wireless transducers. Wireless communication protocol standards such as 802.11 (WiFi), 802.15.1 (Bluetooth), 802.15.4 (ZigBee) are being considered as some of the physical interfaces for IEEE P1451.5. One should be able to get the same sensor data from the wireless sensor implementing any of these three wireless protocols.

IEEE P1451.6 defines a transducer-to-NCAP interface and TEDS using the high-speed CANopen network interface. It defines a mapping of the 1451 TEDS to the CANopen dictionary entries as well as communication messages, process data, configuration parameter and diagnosis information. It adopts the CANopen device profile for measuring devices and closed-loop controllers.

The Fieldbus System

The digital communication network used to link field devices to measurement and control systems is commonly known as fieldbus. This network is serial, bi-directional and multidrop, and will replace the existing star connection between the control system and the sensors-actuators system. Twisted pairs, coaxial cables or optical fibers are used.

There are some key reasons that users are looking to move to standardized industrial network, for the total plant monitoring and control:

- multidrop wiring reduces the installation costs, compared with point-to-point wiring, such as 4 to 20 mA;
- the transmission of digital data decreases the noise sensitivity;

- the use of standard protocols simplifies to integrate in a system instrumentation from several vendors;
- it is possible to condition the signal, e.g. processing the acquired signal to:
- correct systematic errors, e.g. by linearizing the transfer characteristic of the input conditioning and conversion stages;
- compensate the offset errors by an autocalibration procedure, to improve the long-term stability;
- filter the signal by implementing signal processing algorithms;
- it is possible to process the raw measured data in the sensor site, to extract the required information (indirect measurement) reducing the transfer rate and the central processing;
- it is possible to embody autodiagnosis functions in the field devices;
- it is possible to remotely configure the system.

Multiple variables from each device can be brought into the plant control system for archival, trend analysis, process optimization studies and report generation.

The fieldbus system will help manufacturing plants keep up with increasingly stringent safety requirements. By providing operators with earlier notification and warning of pending and current hazardous conditions, fieldbus allows for corrective actions before an unplanned shutdown.

The Fieldbus Model. The International Standards Organisation (ISO), a group responsible for providing industry standards, has created a reference seven-layer model for open system interconnections (OSI model) (18). It explains the various layers of network technology, specifying services and protocols for each of them. Even if this model can appear a little abstract, it represents a good way to describe a digital network.

The layers are called Physical (1), Data Link (2), Network (3), Transport (4), Session (5), Presentation (6) and Application (7). Transport protocols are located in layers 1 to 4. The user-related communications are in layers 5 to 7.

The fieldbus standards do not specify the layers 3 to 6, conceived for long-distance or wide-branched networks. This streamlined architecture ensures fast and efficient data transmission. The layers considered are so the Physical (1), Data Link (2) and Application (7). Moreover a further layer, the User layer (8), is included (Fig. 11).

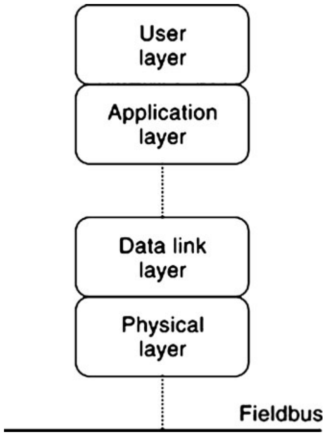

Figure 11. The fieldbus interconnection model.

The Physical layer defines the implementation of device drivers and communication hardware, including the transmission line.

The Data Link Layer establishes and controls the physical path of communication from one node to the next, with error detection. It provides for transparent transmission of Data Link layer entities across physical connections.

This layer does not add anything to the message frame. It simply converts the digital message received from the data link layer into a string of ones and zeroes, represented by a signal on the media. One example is the RS-485, where a binary 1 is represented by a Mark, or Off state, and a binary 0 is represented by a Space, or On state. A Mark is a negative voltage between terminals on the generator, while a Space is a positive voltage on those terminals. The Data link layer defines a mechanism for creating an error-free communications path between devices linked by a physical line. It is defined by the IEEE 802 standard, incorporated by the ISO, which includes two sublevels:

- Logical Link Control (LLC), which defines the same access to layer 7 for all kind of network;
- Medium Access Control (MAC), which defines the techniques to access the medium using the Master/Slave, CSMA/CD, Token Bus, Token Ring procedures.

The Application layer defines the format of the messages, which all devices connected to the network must understand, and specifies the services for process control (e.g. alarm management) supplying them to the User layer. The Application Layer is the most intuitive because it is what the user sees. Internet browsers and e-mail programs are good examples: they allow the user to input and read data while connected between a client PC and a server somewhere on the Internet. In an industrial application, a program on a PLC (Programmable Logic Controller) that controls a smart valve is another one.

The User layer defines the connections between the individual plant areas and provides an environment for applications. It is implemented using high-level control functions.

The extreme layers are the most important, because they are those to which the user must directly interact. The other ones must guarantee a fast and reliable communication, but they are transparent for the user.

The Main Field Bus Standards. The growing international market competition asks for transmission standards to provide a standard interface to facilitate communications between equipment from different manufacturers.

With interoperability, a similar device can replace one fieldbus device with added functionality from a different supplier on the same fieldbus network while maintaining specified operations. This permits users to mix and match field devices and host systems from various suppliers.

Individual fieldbus devices can also transmit and receive multivariable information, and communicate directly with each other, allowing new devices to be added without disrupting active control.

The complete interchangeability and interoperability between different suppliers was not a simple task. The system suppliers introduced the main difficulties with the aim to protect their market, constituted by proprietary installed products, against product interoperability. But the problem is also related to the actual difficulties to standardize a bus, which was primarily considered for linking devices involved in the process automation and successively for the factory automation, building automation and, in some cases, vehicle applications.

There are many different needs for industrial applications. In addition to general requirements (transmission security, distance to be covered or transmission speed), other factors must be considered. As an example, when applications for process automation are involved, data and power must also be transmitted on one common cable.

In an effort to establish a single international fieldbus standard, a number of protocols are used today. Some of them have been developed as national or international standards. Others are proprietary standards. There are at least 3,000 manufacturers of sensors and actuators and at least 50 different network implementations. This means that most of the devices for industrial applications are designed to operate in a special network, limiting their wider applicability and requiring a special gateway to interconnect heterogeneous systems. The features of each of these solutions cannot satisfy the requirements of all the fieldbus applications. In the following the main networks diffused in industrial applications are described.

CAN Network. The CAN (Controlled Area Network) is a shared broadcast bus, primarily used for automotive applications and nowadays for many embedded control applications. This standard specifies only the lower layers 1 and 2. The user must implement layer 7. The access to the transmission bus is carried out implementing the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) technique, quite similar to the widely used CSMA/CD (Carrier Sense Multiple Access with Collision Detection).

CAN presents low connection costs and a secure data transfer, with a speed ranging from 100 kbit/s to 1 Mbit/s, using RS-485 transmission. It is based on sending messages (frames), which are of variable length, between 0 and 8 bytes, protected by a CRC-15. Each frame has an identifier, which must be unique. Two versions of the CAN protocol exists: CAN 1.0 and CAN 2.0 (part A and part B). With CAN 1.0 and CAN 2.0A the identifiers are 11 bits long. With CAN 2.0B identifiers can be 11-bits (standard) or 29-bits (extended) long. The CAN controller architecture is not specified. There are, though, two general approaches, which differ in the buffering of messages.

The controllers with a simple architecture typically present a single transmit buffer and a double-buffered receive buffer. The CPU manages the transmission and reception with interrupt signals and handles the storage of the frames.

More complex controllers can store a limited number of frames (typically 16). Because there can be many more frames on the network, each buffer is tagged with the identifier of the frame mapped to the buffer. The CPU can update a frame in the buffer and mark it for transmission; buffers can be examined to see if a frame with a matching identifier has been received. This provides a set of shared variables in the network; updated and examined by the CPU.

The automotive industry is making extensive use of CAN in new car, bus and truck models.

CANopen is a CAN-based higher layer protocol. It was developed as a standardized embedded network with highly flexible configuration capabilities. CANopen was designed for motion-oriented machine control networks, such as handling systems. By now it is used in many various fields, such as medical equipment, off-road vehicles, maritime electronics, public transportation, building automation, etc. The CANopen communication profile was based on the CAN Application Layer (CAL) protocol. Version 4 of CANopen (CiA DS 301) is standardized as EN 50325-4 (19).

DeviceNet Network. DeviceNet is a network designed to connect industrial devices such as sensors and actuators to higher-level controllers, widely used in manufacturing applications. It is especially used in North American and in Japan. About 140 companies, grouped in an independent supplier organization, the Open DeviceNet Vendors Association (ODVA), support it. This protocol is an extension of the CAN (20).

IEC Standards. Several standards have been defined by the IEC (International Electrotechnical Commission) in this field (21). A list of the most important is reported in the following.

- IEC 60381-1 “Analogue signals for process control systems. Part 1: Direct current signals”. It is applicable to analog direct current signals used in industrial measurement and control systems to transmit. Does not apply to signals used entirely within an element.
- IEC 60381-2 “Analogue signals for process control systems. Part 2: Direct voltage signals”. It is applicable to analog direct voltage signals used in industrial process measurement and control systems. It specifies ranges of analog direct voltage signals, the signal common and the ripple content. The analog direct voltage signal, unlike the analog direct current signal specified in IEC 60381-1, is not intended for transmission over long distances. This standard does not apply to signals used entirely within an element.
- IEC 60625-1 “Programmable measuring instruments - Interface system (byte serial, bit parallel) - Part 1: Functional, electrical and mechanical specifications, system applications and requirements for the designer and user”. It applies to an interface system used to interconnect both programmable and non-programmable electronic measuring apparatus and accessories. It specifies device-independent require-

ments, which need to be met in order to interconnect and communicate unambiguously. Permits apparatus with a wide range of capabilities to be connected to the system. Enables the interconnection of independently manufactured apparatus into a single functional system.

- IEC 61003-1 “Industrial-process control systems - Instruments with analog inputs and two- or multistate outputs - Part 1: Methods of evaluating the performance”. Applies to pneumatic and electric industrial-process instruments using measured values that are continuous signals. Specifies uniform methods of tests for the evaluation of the performance.
- IEC 61131-1 “Programmable controllers - Part 1: General information”. Applies to controllers and associated peripherals. Establishes definitions and identifies principal characteristics relevant to the selection and application of programmable controllers.
- IEC 61131-2 “Programmable controllers - Part 2: Equipment requirements and tests”. Specifies electrical, mechanical and functional requirements as well as the test methods and procedures to be used for the verification of compliance with these.
- IEC 61131-3 “Programmable controllers - Part 3: Programming languages”. Applies to the printed and displayed representation, using characters of the ISO/IEC 646 character set, of the programming languages to be used for programmable controllers.
- IEC/TR3 61131-4 “Programmable controllers - Part 4: User guidelines”. Provides guidelines that address the application of the programmable controllers (PC) and associated peripherals. It also deals with the integration of PCs into the automated system. Provides information that assists the user in: utilizing the other parts of the programmable controller standard, specifying the requirements for PC applications and selecting and implementing PC systems.
- IEC 61158-2 “Fieldbus standard for use in industrial control systems - Part 2: Physical layer specification and service definition”.
  Specifies the requirements for Fieldbus component parts. Also specifies the media and network configuration requirements necessary to ensure agreed levels of:
  - ○ data integrity before Data Link error checking;
  - ○ interoperability between devices at the Physical Layer.
- IEC 61491 “Electrical equipment of industrial machines - Serial data link for real-time communications between controls and drives”. Defines a real-time optical serial interface between the control unit and its associate drives, which is utilized to transmit periodic and nonperiodic data.
- IEC 1158-2. This transmission standard meets the requirements of the chemicals and petrochemicals industries, permitting intrinsic safety and allowing the field devices to be powered over the bus. This is a bit-synchronous protocol, often referred to as H1. Transmission is based on the following principles.

Each segment has only one source of power; no power is fed to the bus when a station is sending. The field devices act as passive current sinks. The passive line termination is performed at both ends of the main bus line. Linear, tree and star networks are allowed. To increase reliability, redundant bus segments can be designed. For modulation it is assumed that a basic current of at least 10 mA is required by each bus station to supply the device. The sending device generates communication signals by modulation from ±9 mA to the basic current. In Table 4 the main features of IEC 1158-2 transmission standard are reported.

IEEE 802 Standards. The IEEE 802 is the foundation document for the series of IEEE 802 Standards for Local and Metropolitan Area Networks (LAN/MAN). It contains key concepts, descriptions of the networks considered, as well as a reference model for protocol standards. These standards include:

- LAN/MAN Bridging & Management (802.1)
- Logical Link Control (802.2)
- CSMA/CD Access Method (802.3)
- Token-Passing Bus Access Method (802.4)
- Token Ring Access Method (802.5)
- DQDB Access Method (802.6)
- Broadband LAN (802.7)
- Integrated Services (802.9)
- LAN/MAN Security (802.10)
- Wireless (802.11)
- Demand Priority Access Method (802.12)
- Wireless Personal Area Networks (WPANs), (802.15).

The Media Access Control (MAC) Bridges package includes IEEE Stds 802. 1j (1996) and 802.3k (1992) [ISO/IEC 10038 (1993)]. In particular, as the fieldbus is concerned, the more interesting standards are the 802.1 and 802.2:

- 802. 1B (1992). Information technology. Telecommunications and information exchange between systems. Local and metropolitan area networks. Common specifications. LAN/MAN management. This edition incorporates a supplement that describes a mechanism for the dynamic discovery of manager and agent stations within a LAN/MAN environment.
- 802. 1D (2004). Information technology. Telecommunications and information exchange between systems. Local area networks. Media access control (MAC) bridges. This edition incorporates transparent bridging between Fiber Distributed Data Interface (FDDI) LANs and IEEE 802 LANs and an annex on source-routing transparent (SRT) bridges. A spanning tree algorithm and protocol ensure a loop-free topology and provide redundancy.
- 802. 1E (1990). Information technology. Telecommunications and information exchange between systems. Local and metropolitan area networks. Common specifications. System load protocol. This edition incorpo-

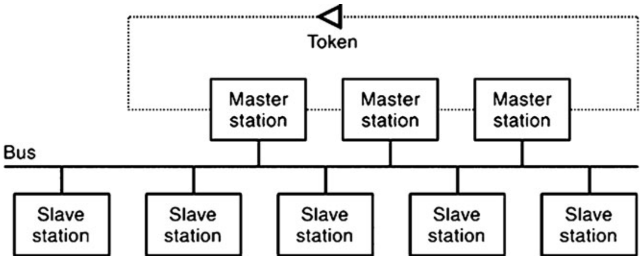

Figure 12. PROFIBUS network.

rates the specification of managed objects that permit the operation of the load protocol to be remotely managed.

- 802. 1F (1993). IEEE Standards for Local and Metropolitan Area Networks: Common Definitions and Procedures for IEEE 802 Management Information.
- 802.1H (1995). Information Technology. Telecommunications and information exchange between systems. Local and metropolitan area networks. Technical reports and guidelines. Media Access Control (MAC) Bridging of Ethernet V 2.0 in IEEE 802 Local Area Networks.
- 802. 1j (1996), supplement to IEEE 802. 1D (1990). Information technology. Telecommunications and information exchange between systems. Local area networks. Media access control (MAC) bridges. Managed Objects for MAC Bridges.
- 802.6k (1992) Supplement to IEEE 802. 1D (1990), IEEE Standard 802.6 Distributed Queue Dual Bus (DQDB) Subnetwork of a MAN.
- 8802-2 (1989). Information processing systems - Local area networks - Part 2:logical link control.

PROFIBUS Network. PROFIBUS (PROcess FIeld BUS) is a family of industrial communication protocols widely used in Europe for manufacturing process and building automation. They are specified as German National Standard DIN 19245 and European Fieldbus standard EN 50170. They have been used successfully, with over 14 million installed devices around the world.

PROFIBUS distinguishes between master and slave devices. Masters (active stations) determine the data communication on the bus. A master can send a message without an external request when it holds the bus access rights (token). The token is transmitted around the stations with a preconfigured temporisation and their possession enables the station to transmit data (Fig. 12).

Slaves (passive stations) are peripheral devices, typical input/output device, valves, drives and measuring transmitters. They do not have bus access rights and can only acknowledge received messages or send messages to the master when requested to do so. Since they only require a small portion of the bus protocol, their implementation is at low cost.

PROFIBUS is a high secure standard, because of the acknowledgement on the data reception, even if the protocol overhead reduces the data rate. The length can range from 0.2 to 1.2 km, with a maximum of 4.8 km with 3 repeaters. The maximum number of devices is 32 (127 with repeaters). It can be used for both high-speed time critical data transmission and extensive complex communication tasks.

The PROFIBUS family consists of three compatible versions.

- PROFIBUS-DP. Optimized for high-speed and inexpensive hook-up, this version is designed especially for communication between automation control systems and distributed I/O, at the device level. PROFIBUS-DP uses layer 1 and 2, and the user interface. RS 485 transmission technology or fiber optics are available for data transmission. RS 485 (referred as H2) is used for high transmission speed and inexpensive installations. Fiber optics are used in environments with high electromagnetic interference. Two types of conductors are available. Plastic fibers for less than 50 m or glass fibers for less than 1 km.
- PROFIBUS-FMS is the general-purpose solution for communication tasks at the production management level. It can also be used for extensive and complex communication tasks. The application layer consists of FMS (Fieldbus Message Specification) and LLI (Lower Layer Interface). FMS contains the application protocol and provides the user communication services. LLI implements the various communication relationships and provides FMS with device-independent access to layer 2. Layer 2, the Fieldbus Data Link (FDL), implements bus access control and data security. DP and FMS use the same transmission technology and a uniform bus access protocol. Thus, both versions can be operated simultaneously on the same cable.
- PROFIBUS-PA is designed especially for process automation. According to the IEC 1158-2, this version permits intrinsic safety data communications and also allows the field devices to be powered over the bus using 2-wire technology. PA devices can be easily integrated in DP networks using a segment coupler to adapt RS 485 signals to the IEC 1158-2 signals. PA offers both tree and line network configurations. The line structure permits the bus cable to be looped through the field devices. Branches for connection of one or more field devices are also possible. The tree structure can be compared to the classic field installation technique.

ISA SP50 network. Since the mid 1980s the Instrument Society of America (ISA), the International Electrotechnical Commission (IEC), have made joint efforts to define a unified fieldbus standard. The ISA, the IEC, the Profibus association and the FIP association constituted the IEC/ISA SP50 Fieldbus committee. The purpose was to define a common standard for signals (analog or digital) used in process measurement and control, to transmit information between subsystems or separated elements of systems. The obstinacy of suppliers to protect their products, united to the actual difficulties, made this task hard.

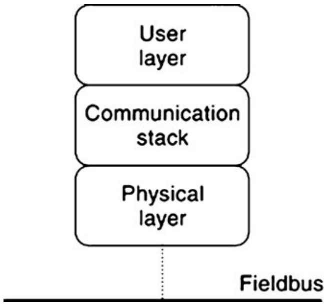

Figure 13. Fieldbus Foundation model.

The result was the standardization of only the Physical level of the bus, reported in the SP50 standard, which includes 31.25 kbit/s, 1 Mbit/s and 2.5 Mbit/s data transfer rates.

Fieldbus Foundation Network. The Fieldbus Foundation is a worldwide consortium constituted in 1994, by a merger of WorldFIP North America and the ISP (Interoperable Systems Project). Actually this organization consists of over 350 leading process and manufacturing automation companies worldwide, with 700,000 devices currently in service, and over 10,000 fieldbus systems. First aim of this organization was the design of a network compatible with the ISA SP50 standards and the specifications of the IEC, such as PROFIBUS, FIP and HART. The open, nonproprietary Fieldbus Foundation specification is based on the ISO/OSI model, and consists of: the Physical layer, the communication stack and the User layer (Fig. 13). The term stack refers to pieces of the OSI model that are bundled together.

The Physical layer corresponds to the IEC Physical layer specification.

The Communication stack corresponds to OSI layers 2 and 7. Layer 7, the Application layer (AL), encodes and decodes User layer commands. Layer 2, the Data Link layer (DLL), controls transmission of messages onto the fieldbus through layer 1. It also manages access to the fieldbus through the deterministic centralized bus scheduler Link Active Scheduler (LAS). The LAS is used for scheduling transmissions of deterministic messages and authorizing the exchange of data between devices. This architecture provides for robust synchronous control, and supports asynchronous communication of data. Asynchronous transmissions can be performed without interrupting the synchronous ones. Data Link capability provides an enhanced access control method, as well as some services including the client/server. On-line device detection and configuration is feasible.

The Foundation provided the H1 and HSE specifications.

Foundation H1 is intended primarily for process control, field-level interface and device integration. Running at 31.25 kbit/s, the technology interconnects devices such as transmitters and actuators on a field network. H1 is designed to operate on existing twisted pair instrument cabling with power and signal on the same wire. Fiber optic media is optional. It also supports Intrinsic Safety (IS) applications.

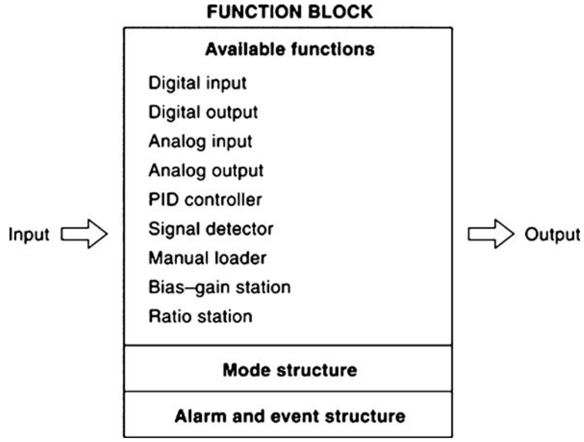

Figure 14. Function-block structure.

A unique characteristic of Foundation H1 devices is the use of Function Blocks, a method for modelling and configuring standard control functions, executed by the devices. The User layer defines a Function Block Application Process (FBAP) using the Resource Blocks, Function Blocks, Transducer Blocks, System Management and Network Management.

Blocks are incorporated into fieldbus devices to achieve the desired device functionality. The block parameters are object descriptions that define how the parameters are transmitted on the fieldbus network.

Resource Blocks define parameters that pertain to the entire application process (e.g. manufacturing ID, device type, etc.).

Function Blocks specify a set of input and output, a Mode Structure (e.g. manual, auto, . . .) and an Alarm/Event Structure (Fig. 14). They embody control functions (e.g. PID controller) and *Transducer Blocks* to interface sensors.

The *Function Block Application Process* is an application model that, in conjunction with the protocol, allows devices from different suppliers to interoperate. A fieldbus device must have a Resource Block and at least one Function Block with input and/or output parameters. Each input/output parameter has a value and a status. In addition, the FBAP specifies the handling of control modes, alarms, events, trend reports and views. The System Management and Network Management manage the function block execution and communication.

The HSE (High Speed Ethernet) is designed for use as a control backbone. Running at 100 Mbit/s, the technology enables device, subsystem and enterprise integration. It supports the entire range of fieldbus capabilities, including standard function blocks and Device Descriptions (DDs), as well as application-specific Flexible Function Blocks (FFBs) for advanced process and discrete/hybrid/batch applications. HSE supports complex logic functions, such as those performed by Programmable Logic Controllers (PLCs), or data-intensive process devices, such as analyzers and gateways to other networks. HSE enhances access to H1 fieldbus technology via linking devices, while providing expanded capabilities for high-speed automation devices and hybrid/batch applications.

The Device Description is a method used by the control system to obtain messages from field devices. Device Description (DD), present in the HART protocol, enables interoperability. It is used to describe standard block parameters and supplier parameters. Specifically vendor name, software revision, implemented function blocks and diagnostic capabilities can be read from the device by any host. The electronic data sheet can be automatically uploaded for the automatic identification of network modules and autoconfiguration, to make system installation, configuration and maintenance extremely simple. In this way, when a module is replaced, the network automatically reconfigures the module.

Suppliers write DDs is a special C-like programming language called Electronic Device Description Language (EDDL). EDDL source code is converted into a binary form used as a driver for a fieldbus device. The Fieldbus Foundation provides DDs for all standard Blocks.

The Foundation protocol is designed to be compatible with the officially sanctioned SP50 standards project of the ISA, as well as and the specifications of the International Electrotechnical Committee (IEC). Since its founding, the Fieldbus Foundation has made compliance with the ISA/IEC standards a priority.

Industrial Ethernet is the name given to the use of the Ethernet protocol in an industrial environment. This solution has been recently proposed and sustained by the IAONA (Industrial Automation Open Networking Alliance), which purpose is to support the international propagation of open networking standards of the IT technology such as Ethernet in automation systems (22). Ethernet is the most popular physical layer LAN technology in use today, because of its balance between cost, data rate and ease of installation and wide acceptance in the computer marketplace.

The standards IEEE 802.3 (23) define rules for configuring a network as well as specifying how elements interact with one another. This standard provides functionality at the OSI physical and data link layers. The MAC allows independent transmission by all nodes of the network. A node sends a message with data, addressing, and control bits. All other nodes analyze the message, but only the node with the destination address will receive and acknowledge it.

This solution has been feasible by the easy migration from the data-rate of 10 Mbyte/s to 100 Mbyte/s or 1 Gbyte/s. In this way the nondeterministic feature of Ethernet networks has been overcome because the high throughput reduces response time to less than 5 ms, suitable for most applications.

Fieldbus devices will transmit over Ethernet and Internet supports and will be accessible as web-based elements. The widely adopted open protocols are TCP/IP (Transmission Control Protocol/Internet Protocol) and UDP (User Datagram Protocol).

Ethernet Data Acquisition Systems take advantage of existing network infrastructure, lower cost network components and trained staff for networking and application development. Different standards are available.

Profinet IO is an Industrial Ethernet communication protocol based on the IEC 61158 (24) and IEC 61784 (25) that uses the same principles of communication of PROFIBUS-DP. Distributed I/O is connected into communication through this network.

Profinet supports real-time capable process communication as well as open communication via Ethernet TCP/IP, using three protocols:

- TCP/IP, open Ethernet TCP/IP communication without real-time requirements (e.g. Web technology with cycle times up to 100 ms);
- RT (Real-Time), IO data exchange between programmable controllers in Real-Time (1 - 10 ms);
- IRT (Isochronous Real-Time), isochronous real-time communication for synchronized IO data exchange (cycle time $<$1 ms).

PROFINET IO allows for integrating simple decentralized field devices or high-performance motion control applications into the communication. The latter require a time-synchronized setpoint specification within minimum cycle time.

Ethernet Powerlink (EPL) is a deterministic real-time protocol based on the standard IEEE 802.3; the current physical layer is 100BASE-X. This open protocol, managed by the Ethernet Powerlink Standardization Group (EPSG), expands Ethernet with a mixed Polling-and Timeslicing mechanism (26). The main advantages are: guaranteed transfer of time-critica

- l data in very short time with a configurable response time;
- time-synchronisation of all nodes in the network with very high precision of sub-microseconds;
- transmission of less timecritical data in a reserved asynchronous channel.

Modern implementations reach cycle-times of under 200 μs and a time-precision (jitter) of less than 1 μs.

Foundation Fieldbus *High Speed Ethernet* (HSE) is ideally suited for use as a control backbone (27). Running at 100 Mbit/s, this technology is designed for device, subsystem and enterprise integration. It supports the entire range of fieldbus capabilities, including standard function blocks and Device Descriptions (DDs), as well as application-specific Flexible Function Blocks (FFBs) for advanced process and discrete/hybrid/batch applications.

INDUSTRIAL PROCESS CONTROL

As suggested by the name, an industrial process control is a system that, regulating some energy inputs, manages specific physical quantities of a productive process. It is constituted by a group of physical components.

Open-Loop and Closed Loop Control Systems

The simplest way to control an industrial process is to use an open-loop scheme, where a control unit manages the

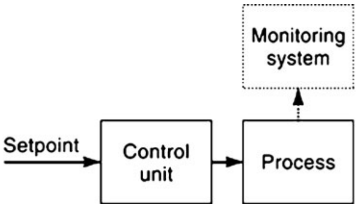

Figure 15. Open-loop control system.

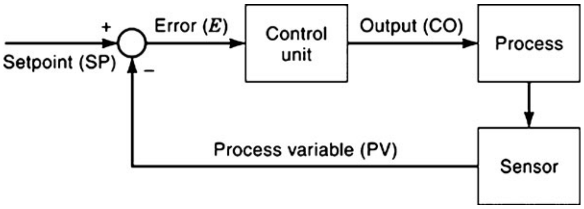

Figure 16. Closed-loop control system.

state of the process by driving some actuators (e.g. valves, motors, pumps, robot arms, electric heaters), as shown in Fig. 15. The state of the process is checked by a monitoring system that measures a process quantity. An input signal (setpoint) manages the control unit. Unfortunately, an open-loop system is sensitive to change in load, to variations in its own parameters and to external disturbances.

The operator can modify the setpoint in response to a change in the measured quantity, to maintain the required process state, closing the loop around the process.

To completely automate the process, a devices that drives the control unit by the difference (error) between the actual measured process variable and the specified setpoint, can be used. This closed-loop (or feedback) control system is shown in Fig. 16. The automatic controllers use actuators to affect the process and sensors to measure the variable quantities.

In this system the controller's output (*CO*) depends and operates in order to automatically reduce the error value, causing some corrective actions on the process. All the tasks of measure, decide and actuate are repeated continuously. The closed-loop controllers are affected considerably less by changes in load or controller gain than the open-loop controllers.

A great number of industrial processes are controlled using a feedback device, using different kind of control units.

On-off and PID Controllers

The simplest type of controller is an on-off device that affects the process by switching on or off the control action (e.g. valve fully open or fully closed). Its main problem is that the process variable can oscillate continuously between its on and off states. Worsening the control unit sensitivity introducing a hysteresis effect can reduce this problem, even if this increases the process variable variation. Another problem is represented by a delay in the variable measurement, which can produce a change in the control output, out of phase with changes in the controlled variable.

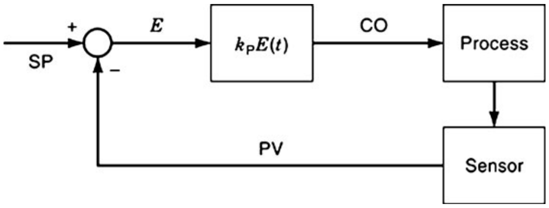

Figure 17. Proportional closed-loop control system.

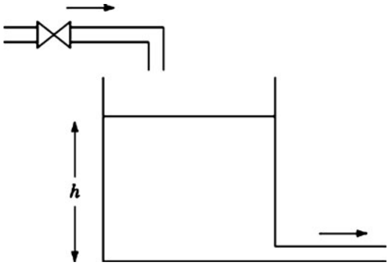

Figure 18. Control of a tank level.

A better approach is to apply to the process a corrective action proportional to the error E between the actual (*PV*) and the required (*SP*) state of the process. The architecture of this system is shown in Fig. 17.

The controller output *CO* is then

$$CO(t) = k_P[SP(t) - PV(t)] = k_P E(t) \tag{1}$$

where the constant k_P is the controller gain.

Because the controller's output changes in proportion to a change in the measured error, this is called a proportional controller.

The increase of k_P has the effect to increase the output *CO*, even if it presents a practical limit relative to the actuator behavior (e.g. maximum valve aperture, maximum motor power). Moreover, the performance of a proportional closed-loop controller with high gain is similar to that of the on-off controller.

A complete regulation is not possible using proportional action control, because it can produce a steady-state error. This can be illustrated with an example. In the system of Fig. 18 a liquid flows into a tank through a pipe, regulated by a restrictor valve, and out through another pipe. A system maintains constant the level h in the tank, using a proportional control action that regulates the filling.

When the level is lower than h the error E increases and the controller open the valve, to produce an inflow. When the level increases, the error decreases reducing the inflow rate. If the level is h, the error is zero and the valve is closed.

For a constant outflow the valve must be partly open in order to produce the same inflow rate. This requires that E must be greater than zero, and therefore that the level cannot be equal to h. A solution can be to increase the setpoint in order to produce the right level at the equilibrium. But if a change occurs in the outflow rate, the measured level changes, generating an error.

In short, there will be always a steady-state offset, because an error is required in order to generate any control signal at all. Since the control signal generated by propor-

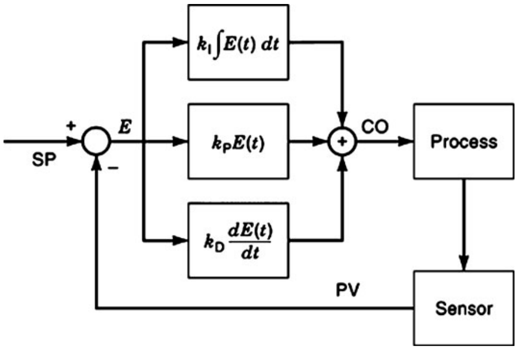

Figure 19. PID control system.

tional action depends also on the gain k_p, the greater the proportional action factor, the less is the offset.

To solve the problem of the offset on the proportional action, an integral (**I**) control action is included, to generate a corrective effort proportional not to the present error, but to the sum (integral) of all previous values:

$$CO(t) = k_I \int E(t)\mathrm{d}t \tag{2}$$

where k_I is a constant.

In this case, when the error is reduced to zero, the output *CO* stops changing and remains constant at a value sufficient to maintain E at zero, so the system does not produce an offset error. However, if the integral action is too strong, it over-corrects for an error, generating a new one in the opposite direction, producing closed-loop instability. To avoid high overshoots and oscillations the gain k_I must be limited, so in many cases a long time it is required to compensate for a process change.

The main drawback of integral control action is that it adds a delay into the control loop that depends on the rate of integration. The effect of an abrupt variation on the measured quantity cannot produce an integral corrective action until after the delay is incurred.

Including a control action proportional to the time derivative (D) of error, can reduce this delay:

$$CO(t) = k_D \frac{\mathrm{d}E(t)}{\mathrm{d}t} \tag{3}$$

where k_D is a constant.

The derivative action generates a large corrective effect immediately after an error change, in order to eliminate it as quickly as possible.

A PID (proportional-integral-derivative) control system, shown in Fig. 19, executes the following control law:

$$CO(t) = k_P E(t) + k_I \int E(t)\mathrm{d}t + k_D \frac{\mathrm{d}E(t)}{\mathrm{d}t}. \tag{4}$$

When a change in the process variable occurs, the error increases and the derivative action grows up, producing a corrective effect. Successively the derivative effect decreases, while the integral and proportional actions operate to completely eliminate the error. The integral action contributes to the controller's output as the error accumulates over, governing the output since the error decreases.

When the process presents a high response time, even after the controller eliminates the error it continues to generate an output based on the accumulation of errors managing the integral action. If the integral action is not too high, this error can be smaller, and the integral action decreases as negative errors are added to the accumulated error. This whole operation may then repeat several times until both the error and accumulated error are eliminated. On the other hand, the derivative action will tend to be larger because the error changes rapidly when the process is highly responsive. The proportional action also will come and acts depending on the error value.

If the controller output *CO* exceeds the actuator capacity (saturation), the integral action grows as the error accumulates over time, until *E* changes sign and the accumulated error begins to diminish. To avoid this problem, the integral action must be limited until *E* changes sign, e.g. holding the last value of integral term.

In some commercial PID controllers the control law can be quite different from (4). As an example in the following relation the derivative term refers to the process variable and not to the error, to avoid discontinuities in the controller's output when the setpoint is changed.

$$CO(t) = k_P E(t) + k_I \int E(t)\mathrm{d}t + k_D \frac{\mathrm{d}PV(t)}{\mathrm{d}t}. \tag{5}$$

Various implementations are commercially available.

PID Tuning. Before applying a PID controller, some arrangement (tuning) to adapt control settings to a specific process are required. A widespread used method to tune PID systems is to observe the behavior of the controlled process and change the proportional (P), integral (I), and derivative (D) parameters until the closed-loop system performs as desired. However, the simplicity of basic PID actions is only apparent. The prediction of the overall behavior when they operate together for a particular application can be difficult, e.g. because it also depends on the process's dynamic behavior.

In some devices an automatic tuning procedure is provided (self-tuning PID). The tuning parameters can be set accordingly to how the process reacts to a series of artificial disturbances applied to the process. The controller measures the process variable, calculates the control effort and determines the setting values.

Other systems use data collected during the normal working, to limit the problems caused by the intentional disturbances, even if it can supply less information about the process.

Commercial PID controllers currently are applied to automate more than 90% of industrial processes. Their main advantages are simplicity of operation, reliability and low-cost. In the majority of application they represent the better solution, even if some industrial processes require more advanced control techniques. Specifically time-varying, non linear or multivariable processes are hard to control using only PID loops. In these cases different techniques can be applied, i.e. multivariable control, adaptive control, expert systems.

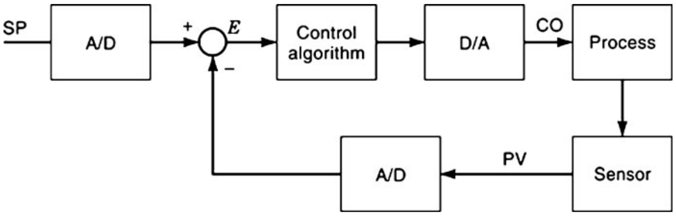

Figure 20. Structure of a digital control system.

Control of Constant Processes

Continuous and Discrete Controllers. In some industrial applications where the process variables can change their value at any instant, continuous controllers are required. These processes can be usually founded in petrochemicals, pharmaceuticals, pulp and paper industries. A continuous controller measures the process variable, then decides if it is at an acceptable level and drives the actuators to control the process, in a continuous way.

In some continuous processes the presence of friction, inertia, and system stiffness prevents a process variable from changing rapidly. The control action can only produce slowly change in its value. In these cases even if the process variable can change continuously, it can be measured and processed only at discrete instants, spaced of a sampling period. If a suitable time interval is selected, within which maintain constant the controller output, comparable results of continuous controllers are obtained. The shorter is the sampling interval, the better is the approximation. On the other hand, in processes like motion control applications, the rapid changes in the position and velocity variables requires very high sampling rates.

There are some particular applications where the process variable may change only at specified time intervals, e.g. because the activities to be controlled occur step-by-step, where each step starts only after its predecessor finishes. For processes like these, fast sampling is not required to a discrete controller.

In the past true continuous controllers was based on mechanical or electrical devices that generate corrective actions on the process by amplifying the forces or voltages generated by the process measuring system. Today continuous controllers are practically out of production and replaced with discrete digital systems.

Computer-based Controllers. A computer-based controller performs a discrete digital control. At a specific instant it measures the process variable, transforms it in a digital form by an A/D converter and compares it with the converted value of setpoint (Fig. 20). The generated digital error E is used to compute the appropriate control actions that, converted by the D/A, is applied to the process. To perform these operations it takes a finite time (sampling interval) and only when it finishes these tasks it returns to reading the sensor.

All the digital controllers are characterized by an absolute time constraint for measuring the process variables, running the parameter estimation and control algorithms and generate the control output to the actuators. Data processing time mainly depends on the required features, that is, on the adopted measurement algorithm and on the processor performance. To meet a variety of performance requirements, different solutions are adopted. High performance systems are generally based on multi-DSP, to provide enough flexibility and scalability to meet system constraints at relatively low costs. In these systems, each DSP conducts a portion of the signal processing, concurrently to the other ones.

In some plants this time constraint can be ignored, because the processes are relatively slow (e.g. time constants of minutes for chemical processes). The control of other processes (e.g. electromechanical) requires sampling periods relatively small (less than 0.1 ms).

Multivariable Controllers. Control techniques based on the measurement of a single variable are applied for a wide variety of industrial processes. In some cases, e.g. in petrochemical industry, different quantities affect the process, such as temperature, pressures and flow rates. In these cases, the control system can use multiple controllers and actuators to affect all of the process variables simultaneously. This technique presents the disadvantage that each device can controls only a process variable. PID controllers are hard to apply in a multivariable process, because it is not simple to tune a controller for each process variable, because of the cross effects of one variable vs the others.

Different multivariable controllers are generally applied. Rather than separate the controllers selecting a suitable setpoint value for each respective process variables, these systems balance the actions of several actuators that affect different process variables, to increase the overall performance.

Control of Non-Constant Processes

Robust and Adaptive Controllers. When the process characteristics vary significantly with time, two solutions can be performed.

The controller can be designed in order to have the best constant parameters that can deal with these variations. This variation-tolerant constant controller is known as robust controller.

The other solution is to design the controller to have parameters that adapt its working behavior to changes in the process under control. This, known as model-based adaptive controller, uses a mathematical model that describes the process behavior by means of mathematical equations. It is used by the controller to predict the better control output to apply to the process. This operation can be performed when the system it is in operation, in order to optimize its behavior. To obtain good results with this technique, a good model of the system is needed, otherwise the closed loop system can show instability.

An adaptive controller can adopt different working strategies.

- The process model changes in a restricted finite number of configurations, for each of which a different constant controller is designed. When a diverse process condition is recognized (e.g. measuring some quantities), the controller is changed consequently. This technique is known as controller scheduling or as preprogrammed control. Strictly speaking this is not an adaptive technique, because each controller presents a constant configuration.

- An on-line algorithm processes input-output data acquired from the system, to estimate the current process model (model identification) (28). This new model is used to implement the new controller (controller design). The system loops, running the model identification and controller design routines.
- A particular fixed mathematical model, known as reference model, is designed. Its behavior represents how the process should operate. Both the reference model and the process receive the same input signals. The comparison between the calculated model output and the measured process variable produces an error signal that forces the process to follow the model output. This controller is known as Model Reference Adaptive Controller (MRAC).

In general, if the process is linear and there are no particular constraints, all the model-based controllers can produce similar results, i.e. one method is no better than another. From a designer's point of view the methods differ in the choice of design parameters and in the design methodology.

An annoying aspect of these techniques is that the mathematical formulation of the control algorithm is complex, compared with PID control. Moreover the implementation of these techniques on a digital controller frequently requires a high-performance computing system.

Models and Modelling

The importance of modelling an industrial process refers to different aspects. A model allows the process to be described in a suitable way and making clear its analogy to systems of different physical nature. At the design stage, a model can be used to determine the preliminary analysis of a design hypothesis, e.g. to analyze some system features before it is built. It can help to reduce time in setting up the control algorithm. Some advanced applications need the adoption of model-based control systems capable of responding properly in real-time to varying working conditions, environment disturbances and parameter variations.

A model is an abstract description in a symbolic language of the process, and then several types of model exist. In the context of this paper, process modelling refers to a mathematical representation.

An important issue is that a model covers only some aspects of the process and does not provide a complete understanding of it. Generally the processes are, or can be considered, linear or lightly non-linear and therefore linearizable. In most cases the parameters are constant. Some parameters depend on environmental quantities, leading to difficulties, especially when an accurate model must be implemented.

Algebraic equations, ordinary differential equations, partial differential equations, integral equations and the like describe the relations between the variables. Laplace transforms are widely applied to reduce differential equations to algebraic ones.

The computer implementation of the analytical model, commonly called software model, is frequently adopted in simulation, measurement and control. When the model is adopted for computer based applications, which must run in real-time, the model needs not to be very sophisticated. However, the trade-off of mathematical complexity vs accuracy of simulation is extremely important.

Model Development. There are two basically approaches to the problem of building an analytical model of a given system. The first one is based on the knowledge of the physical laws and relationships that govern the system's behaviour. This procedure (modelling) is widely adopted, even if often, it may not be possible because the knowledge of the system is incomplete (29, 30).

The second one (identification) deals with the dynamical analytical model building based on observed data from the system (28).

Model implementation is generally carried out in more than one cycle. At the first a model that describe the ideal behavior of the process is assumed. Then a more complex modelling of the real behavior is introduced. Deciding what secondary effects might need consideration requires considerable experience and skill. Process refinement continues until the model provides an adequate level of simulation.

Modelling by Analytical Analysis. The development of a process model starts with the analysis of the process to be modelled, acquiring all relevant information and developing a graphical representation of it (e.g. using a block diagram with linguistic descriptions).

A suitable architecture is then implemented, decomposing large and complex processes into constructional or functional elements, e.g. using a block diagram with a limited number of smaller structures, such as serie, parallel and feedback architectures. Each block transforms a physical input into a physical output for a specified purpose.

For each block the physical laws are analyzed, in order to have a suitable physical relation between the input and output. Because the physiscal behavior is generally known in mathematical terms, a suitable mathematical relation is assigned to each block. The mathematical expressions are integrated into a unified set, to give the overall model of the entire process.

The final step is to provide a means for solving the model equations. In case of a complex model, some simplifications are introduced to facilitate the model solution. Typical example is the linearization of a non linear model to reduce the complexity of solution algorithm.

The last step is the validation phase, that refers to the analysis of conformity of the model to the objectives for which it was implemented, that is the degree of correctness and accuracy to which it represents the real behavior of the process.

Modelling by Empirical Data Analysis. When the physical laws governing the process are unknown, the system model can be evaluated by means of estimation algorithms, starting from input/output measurements of the system, supplied by a suitable input signal. Statistical estimation methods are frequently carried out, because of the noise superimposed on the signal. To apply this technique, generally the model structure (form of model equation) is known from a priori knowledge. Actual measurements are used to estimate the coefficient values that cause the assumed mathematical structure to best fit the data. In other case the identification process must evaluate and choose between a set of model structures (31).

Signal Processing

Algorithmic Signal Processing. As previously stated, for a variety of reasons the signals produced by sensors need to be processed. This is because the electric output should be converted in engineering unit or because more signals should be processed to extract a piece of information, applying sophisticated algorithms. In many cases, the signal is in the form of an analog electrical voltage or current, in others in digital form.

Analog signals can be processed by analog circuits made up from components such as resistors, capacitors and operational amplifiers, to produce the required signal transformation. Typical example of application is the signal filtering.

Digital signals can be processed to perform numerical calculations. The processor may be a general-purpose computer such as a PC, or a specialised DSP (Digital Signal Processor) chip. Analog signals must first be sampled and digitised using an A/D converter, then they are transferred to the processor, which carries out numerical calculations on them. If necessary, the results are output through a D/A converter to convert the signal back to analog form. Digital processing techniques present several advantages, such as programmability, stability, reconfigurability.

Digital processing systems use different techniques. Mathematical computations are generally carried out running a suitable algorithm, based on a mathematical model of the system under analysis. The main drawback of this method is that for a good representation of the process a very complex formulation is frequently required, making so impractical its implementation. As main DSP techniques, Fast Fourier and Hilbert transforms and signal filtering can be mentioned.

Adaptive signal processing is one of the most important classes of algorithms for industrial control. Key application areas are noise cancellation, system identification, inverse system identification and prediction. As an example, Fig. 21 shows the architecture of an adaptive filter. The input signal $x(k)$ is processed by a digital filter, such that the output $y(k)$ is very similar a reference signal $r(k)$. The adaptive algorithms minimizes the power of the error signal $e(k) = r(k) - y(k)$, by minimizing the squared error or the mean squared error.

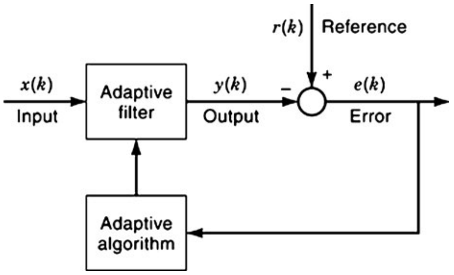

Figure 21. Architecture of an adaptive filter.

Although the mathematical theory underlying DSP techniques can be fairly complex, the numerical operations required to implement these techniques are in fact very simple. Most measurement algorithms require the extended use of arithmetic operation of multiply and add. A suitable processor for these applications is the DSP, specially architectured to accelerate the execution of numerically intensive calculations: it performs single clock cycle multiply-accumulate (MAC) operations. On the contrary, general purpose processors generally require tens of clock cycles for a multiplication.

Model Based Measurements. In modern instruments the information acquired by the sensors is processed by powerful signal processor sub-systems. Raw data that arises from measurement, corrupted by sensor imperfection and environmental influences, can be numerically corrected by applying model-based (inferential) measurement techniques. A suitable mathematical model of the relationship between the measurand and the raw result of measurement is considered. The final result is obtained by estimating the correct value, using a measurand reconstruction based on the inverse of the forward model.

Regarding the model, two forms can be distinguished. In the first case the relation between measurand and directly sensed quantities is implicit (e.g. the measurand is a parameter of the model) and requires the application of an identification process. In the second one the relation is explicit, reducing so the overall amount of calculation. A good statement of this technique is given in (32, 33).

These methods have proved to be extremely effective and useful in certain instruments, even if the most serious limitation in industrial applications is that traditional devices can introduce unwanted latency for the signal processing, which is critical for a control system operating in a closed loop.

In some control applications it is asked for the measurement of quantities which frequently cannot be directly obtained. Applying on-line indirect measurement techniques can solve the problem. As previously stated, this can be achieved by means of an accurate modelling of the physical phenomena involved. The mathematical solution of the model of the system under investigation allows the desired quantities to be indirectly measured.

Knowledge-based Signal Processing. Some problems that cannot be expressed using a formal mathematical formulation, can be solved using the so-called applied intelligence (AI), or artificial intelligence, methods. Their main field of application is that of highly nonlinear processes, where standard algorithms are hard to be implemented and show lower features. Today many application software tools and integrated circuits support this kind of signal processing.

On the contrary of traditional algorithms, the lack of formality of AI techniques makes hard to calibrate and assure their performance. A complete scientific foundation for AI methods has not been developed, even if in the last years they have been extensively applied in industrial products and applications.

These systems use a knowledge in a particular field (e.g. a process) to made a decision (which kind of action execute), starting from some acquired data. A knowledge-based system can be seen as a system that maps many input to one output, applying a decision technique making judgement of the available options. The mapping process is then based on special rules, that are implemented in the software or in the hardware of the system. Another technique is based on the frames, small databases working like objects in object oriented programming. The user must select the parameters used by the system to implement its decision.

Symbolic (or classical) AI is the branch of artificial intelligence research that represents human knowledge in a declarative form (i.e. facts and rules). It is necessary to translate often implicit or procedural knowledge (i.e. knowledge and skills which are not readily accessible to conscious awareness) possessed by humans into an explicit form using symbols and rules for their manipulation. Artificial systems mimicking human expertise (Expert Systems) are widely used in a variety of fields, to solve problems normally thought to require human specialist.

Fuzzy. Fuzzy controllers are rule-based systems, where an inference engine produces logical decisions as consequences of logical rules, from a given rule base which is part of the knowledge base. The control algorithm is represented by a collection of if-then rules.

A fuzzy logic controller can be seen as a small real-time expert system implementing a part of a human operator's expertise. It differs from conventional artificial intelligence expert systems in that the rules are qualitative but the input and output variables usually attain quantitative values. When there is little experience or knowledge about the process and when it is impossible to carry out field test for tuning the controller, fuzzy logic cannot be applied.

Neural Networks. Despite the advantages of the algorithmic approach, it has many problems in some situations. Typical example is to solve a model of a process that is difficult to obtain, partly unknown or highly nonlinear. In these cases a different approach which attempted to mimic human performance within restricted domains of knowledge can be taken, even if a human operator uses various kinds of information and a combination of control strategies that are hard to implement in a controller.

Recent advances in mathematics and understanding the mechanism of learning in addition to the increase in the computing power permit to build artificial neural networks. Using these systems it is possible to implement adaptive sensory modelling and control in a manner similar to the working of human operators. Neural network theory is based on the idea that certain key properties of biological neurons can be extracted and applied to recreate some the computing potentials of the brain.

This technique is based on a system that, after a training phase, learns how operate to make the mapping process, instead of having programmed rules. Using historical data a neural network acquires knowledge by the system under control, learning the process dynamics. During the learning phase a set of input are applied to the network, that modifies its internal weights to generate the required output.

Main advantages of this approach is that the neural networks have nonlinear dependence on parameters, then implement a nonlinear model. They utilize programming commands very different from traditional ones, e.g. behave, react, self-organize, learn, generalize, and forget. However, they are not a solution for all computing problems. Traditional computing methods work well for problems that can be well characterized.

SOFTWARE TOOLS

Software Tools for Embedded Field Devices. A wide range of fieldbus control devices and intelligent instrumentation are today widely diffused in the industrial arena. Low-end, embedded systems are available for plant and factory floor applications. Original equipment manufacturers (OEMs) implement low-cost solutions, e.g. industrial PC, often in compact form factors such as PC-104-Plus, Small PCI or STD. Embedded software (SW) solutions often comply with the user requirements. Different SW operating systems are used, such as Microsoft Windows, Linux (34) and QNX (35) are widely applied for both server and embedded applications. Their principal advantages are:

- networking support and connectivity to nonembedded and enterprise information systems;
- familiar Graphical User Interface (GUI);
- widest range of third-party software components.

Application programs can be implemented writing custom software or buying off-the-shelf packages. In the first case the risks are a wrong choice of the programming platform and a bad implementation of the application program. In the second one an annoying aspect is the flexibility for customization, even if most packages now offer developer toolkits for creation of special features. Practically, these packages allow a user to configure special functions (blocks of code), which are integrated into the application program. More particular application blocks can be written with component software, also referred to as object-oriented languages, such as Visual Basic, C++, or Java. Different blocks can be put into a library and linked to each other to implement the application program.

Windows includes objects based on Component Object Model (COM) and its distributed extension (DCOM), a technology for software components distributed across several networked computers to communicate with each other.

Object Linking and Embedding (OLE) and Dynamic Data Exchange (DDE) can merge data streams from different applications and can communicate with other OLEcompliant softwares. CORBA (Common Object Request Broker Architecture), is an open, architecture and infrastructure that computer applications use to work together over networks. Using a standard protocol, a CORBA-based program from any computer, operating system, programming language, and network, can interoperate with a CORBA-based program running on another computer.

The .NET Framework is a software component which can be added to the Windows operating system to provides pre-coded solutions to common program requirements, and manages the execution of Web Services and Web Applications.

Data acquisition and control systems that use standard LAN/WAN technologies can be accessed using Internet and intranet browsers running HTML, Java or WEB services applications.

Software for Process Monitoring. Automatic process monitoring and data analysis are widely used in the industrial field at the process management and upper levels, to examine the manufacturing of various products. Typical implemented tasks include the:

- monitoring of setpoint, output, and process variables to tune the parameters in PID control loops;
- filtering of process variables, to reduce noise;
- generating an alarm when a process variable reaches a threshold, or when it exhibits certain behaviors, e.g. a rapid change in value;
- plotting one analog variable versus time or versus a second one;
- plotting historical data, including overlaying current data on historical data for analysis;
- comparing sets of measured variables to desired results.

Software-based process monitoring represents an evolution of functions previously performed by an operator watching panel instruments. Numerical or (better) graphical representation of panel instruments can be implemented also at a remote location. Digital and analog indicators, bar-graphs, waveform charts and displays graphs can be easily displayed on a CRT.

Panel instrument replacement is a basic function supplied by all process monitoring software. Other capabilities include the memorization of displayed data for subsequent analysis. Moreover displayed data can be arranged to visualize a physical representation of plant processes. For example the level of liquid in a vessel or the temperature in a furnace can be shown to rise and fall, depending on the value of the corresponding analog variables. The status of various on/off devices can be shown by changing the color of the items, or by animating the display. A pump rotor can be shown to rotate when the pump is active.

Another new powerful technique available with process monitoring software is the emulation of the behavior of specialized laboratory instruments, e.g. oscilloscopes, multimeters and spectrum analyzers. The PC can process the acquired data, which create on the display a virtual instrument capable of equalling or outperforming its real world counterpart. In addition, the virtual instrument can simultaneously emulate many different types or instruments, resulting in substantial cost savings (36).

Mathematical Manipulation. Sophisticated mathematical data manipulation software opens up an entirely new realm of data analysis and presentation. Supervisory and management systems process row data from the field devices to extract information. This task often requires the derivation of mathematical relationships, either among data or between data and other parameters.

Statistical analysis is widely used for both quality acceptance and control, and statistical process control (SPC). The most common analyzed parameters are the mean, the standard deviation, the range, the moving average, the moving range, and the cumulative sum. Other statistical functions include Chi-square analysis, Pareto analysis, distribution analysis, nonparametric analysis, correlation, single variable regression, multiple linear regression and random number generation. Many different types of control charts can be generated including X-bar, R-bar, histograms, and probability plots. These functions and charts are used in a wide variety of industrial applications. Many software programs are available to perform these types of functions.

The process monitoring programs produce alarms to show a single unacceptably low or high value. Unacceptable values could also be anticipated by alarming certain conditions such as successive values trending towards a boundary limit. Anticipation of an alarm condition could allow plant operations personnel to correct a problem before it occurs. Many of these software programs were originally written for applications not involving data acquisition (data were entered manually or imported from a file). Fortunately, there are hardware and software methods available to solve this problem.

Acronyms ac: Alternating Current
A/D: analog-to-digital
AES: Advanced Data Encription
AI: Applied (or Artificial) Intelligence
AL: Application layer
ANSI: American National Standard Institution
CAL: CAN Application Layer
CAN: Controlled Area Network
CCK: Complementary Code Keying
CIM: Computer Integrated Manufacturing
CIP: Computer Integrated Processing
CO: Controller Output
COM: Component Object Model
CORBA: Common Object Request Broker Architecture
CPU: Central Processing Unit
CRC: Cyclic Redundancy Check
CRT: Cathode Ray Tube
CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD: Carrier Sense Multiple Access with Collision Detection
DSP: Digital Signal Processor
DSSS: Direct Sequence Spread Spectrum
D/A: digital-to-analog
dc: Direct Current

DCOM: Distributed Component Object Model
DD: Device Description
DDE: Dynamic Data Exchange
DDL: Device Description Language
DLL: Data Link Layer
DSP: Digital Signal Processor
DSSS: Direct Sequence Spread Spectrum
E: Error
EDDL: Electronic Device Description Language
EPL: Ethernet Powerlink
EPSG: Ethernet Powerlink Standardization Group
EIA/TIA: Electronic Industries Alliance/Telecommunications Industry Association
EMC: electromagnetic compatibility
FBAP: Function Block Application Process
FDDI: Fiber Distributed Data Interface
FDL: Fieldbus Data Link
FFB: Flexible Function Block
FIP: Factory Information Protocol
FMS: Fieldbus Message Specification
FSD: Frame Start Delimiter
FSK: Frequency Shift Keying
f/V: frequency to voltage converter
GUI: Graphical User Interface
HART: Highway Addressable Remote Transducer
HSE: High Speed Ethernet
HTML: HyperText Meta Language
IAONA: Industrial Automation Open Networking Alliance
IEC: International Electrotechnical Commission
IEEE: The Institute of Electrical and electronics Engineers
IFG: International Fieldbus Consortium
I/O: Input/Output
IRT: Isochronous Real-Time
ISA: Instrument Society of America
ISM: instruments, scientific and medical
ISO International Standards Organisation
ISP: Interoperable System Project
I/V: current to voltage converter
LAN: Local Area Network
LAS: Link Active Scheduler
LLC: Logical Link Control
LLI: Lower Layer Interface
MAC: Medium Access Control
MAN: Metropolitan Area Network
MIC: Message Integrity Check
MMI: Mixed Mode Interface
MMT: Mixed Mode Transducer
MRAC: Model Reference Adaptive Controller
MSTIM: Mixed-Mode Smart Transducer Interface Module
NCAP: Network Capable Application Processor
NIST: National Institute of Standards and Technology
ODVA: Open DeviceNet Vendors Association
OEM: Original Equipment Manufacturers
OFDM: Orthogonal Frequency Division Multiplexing
OLE: Object Linking and Embedding
OSI: Open System Interconnections
PAM: Pulse-Amplitude Modulation
PC: Personal Computer
PC: Programmable Controller (especially before IBM used the term PC for their computer)
PCM: Pulse-Code Modulation
PDM: Pulse-Duration Modulation
PPM: Pulse-Position Modulation
PI: Proportional Integral
PID: Proportional Integral-Differential
PLC: Programmable Logic Controller
PROFIBUS: PROcess FIeld Bus
PV: Process Variable
RF: Radio Frequency
RT: Real-Time
RTD: Resistance Temperature Detector
SDLC: Synchronous Data Link Control
SP: Setpoint
SPC: Statistical Process Control
SPI: Serial Pheriperal Interface
SRT: source-routing transparent
STIM: Smart Transducer Interface Module
SW: Software
T: Transducer
TBIM: Transducer Bus Interface Module
TCP/IP: Transmission Control Protocol/Internet Protocol
TEDS: Transducer Electronic Data Sheet
TII: Transducer Independent Interface
UDP: User Datagram Protocol
V/f: Voltage to frequency converter
V/I: Voltage to current converter
WEP: Wired Equivalent Privacy
WorldFIP: World Factory Information Protocol
WPAN: Wireless Personal Area Networks

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